

TEMPERATURE DEPENDENCE OF ATTITUDE SENSOR COALIGNMENTS ON THE SOLAR MAXIMUM MISSION (SMM)*

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ABSTRACT

This paper presents results on the temperature correlation of the relative coalignment between the fine-pointing Sun sensor (FPSS) and fixed-head star trackers (FHSTs) on the Solar Maximum Mission (SMM). This correlation can be caused by spacecraft electronic and mechanical effects.

Routine daily measurements reveal a time-dependent sensor coalignment variation. The magnitude of the alignment variation is on the order of 120 arc-seconds (arc-sec), which greatly exceeds the prelaunch thermal structural analysis estimate of 15 arc-sec. Differences between FPSS-only and FHST-only yaw solutions as a function of mission day are correlated with the relevant spacecraft temperature. If unaccounted for, the sensor misalignments due to thermal effects are a significant source of error in attitude determination accuracy. Prominent sources of temperature variation are identified and correlated with the temperature profile observed on the SMM.

It has been determined that even relatively small changes in spacecraft temperature can affect the coalignments between the attitude hardware on the SMM and the science instrument support plate and that frequent recalibration of sensor alignments is necessary to compensate for this effect. An alternative to frequent recalibration is to model the variation of alignments as a function of temperature and use this to maintain accurate ground or onboard alignment estimates. These flight data analysis results may be important considerations for prelaunch analysis of future missions.

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1. INTRODUCTION

This paper presents the Solar Maximum Mission (SMM) flight system measurement of the correlation between the spacecraft structure temperature and the coalignment of the fine attitude sensors, composed of two Adcole fine-pointing Sun sensors (FPSSs) and two Ball Aerospace CT401 fixed-head star trackers (FHSTs). An overview of the SMM, including mission history and configuration, is presented. Possible causes of the variation in the coalignment, subsequently referred to as the misalignment, are discussed, and the conclusion is drawn that the spacecraft temperature is the predominant factor affecting the FPSS-FHST misalignment. Two methods of compensating for this misalignment, frequent in-flight calibration and misalignment function modeling, are compared with regard to accuracy and impact to science data collection. This work was done by the Flight Dynamics Division (FDD) attitude determination and control ground support team, working in the Flight Dynamics Facility (FDF) at Goddard Space Flight Center (GSFC).

1.1 MISSION HISTORY

The SMM was launched in February 1980 from the Eastern Test Range at Kennedy Space Center (KSC), into an approximately circular low-Earth orbit, with an inclination of nearly 28 degrees (deg) (Reference 1). The scientific objective of the mission was to study solar phenomena. The spacecraft attitude system provided three-axis stabilization and supported solar feature targeting. The spacecraft functioned normally until November 1980, when the standard reaction wheel (SRW) package that provides the controlling torques to the spacecraft began to fail. To preserve the mission, the SMM was put into a spin (≈ 1 deg per second) about the minor principal axis in which it remained until April 1984. With the spacecraft in the spin mode, only minimal solar observation was possible. During April 1984, the spacecraft was repaired in-orbit by the Space Transportation System (STS). The entire attitude control system was replaced, and the spacecraft was returned to the nominal scientific observing mode.

1.2 MISSION CONFIGURATION

The SMM was the first of the multimission modular spacecraft (MMS) series. The MMS were modular to facilitate mission repair and mission adaptation. The SMM basically consists of two parts as shown in Figure 1: the MMS itself and the experiment module. The modules that come with the MMS series are

- A Command and Data Handling (CD&H) system that handles all the communications between the ground and the spacecraft and includes the spacecraft on-board computer (OBC)
- A Modular Power System (MPS) that operates all the power systems, including the Solar Array System (SAS)
- A Modular Attitude Control System (MACS) that contains most of the sensors used in the attitude determination and control of the spacecraft. A High-Gain Antenna System (HGAS), for use in communicating with the Tracking and Data Relay Satellite System (TDRSS), is also attached to the end of the spacecraft.

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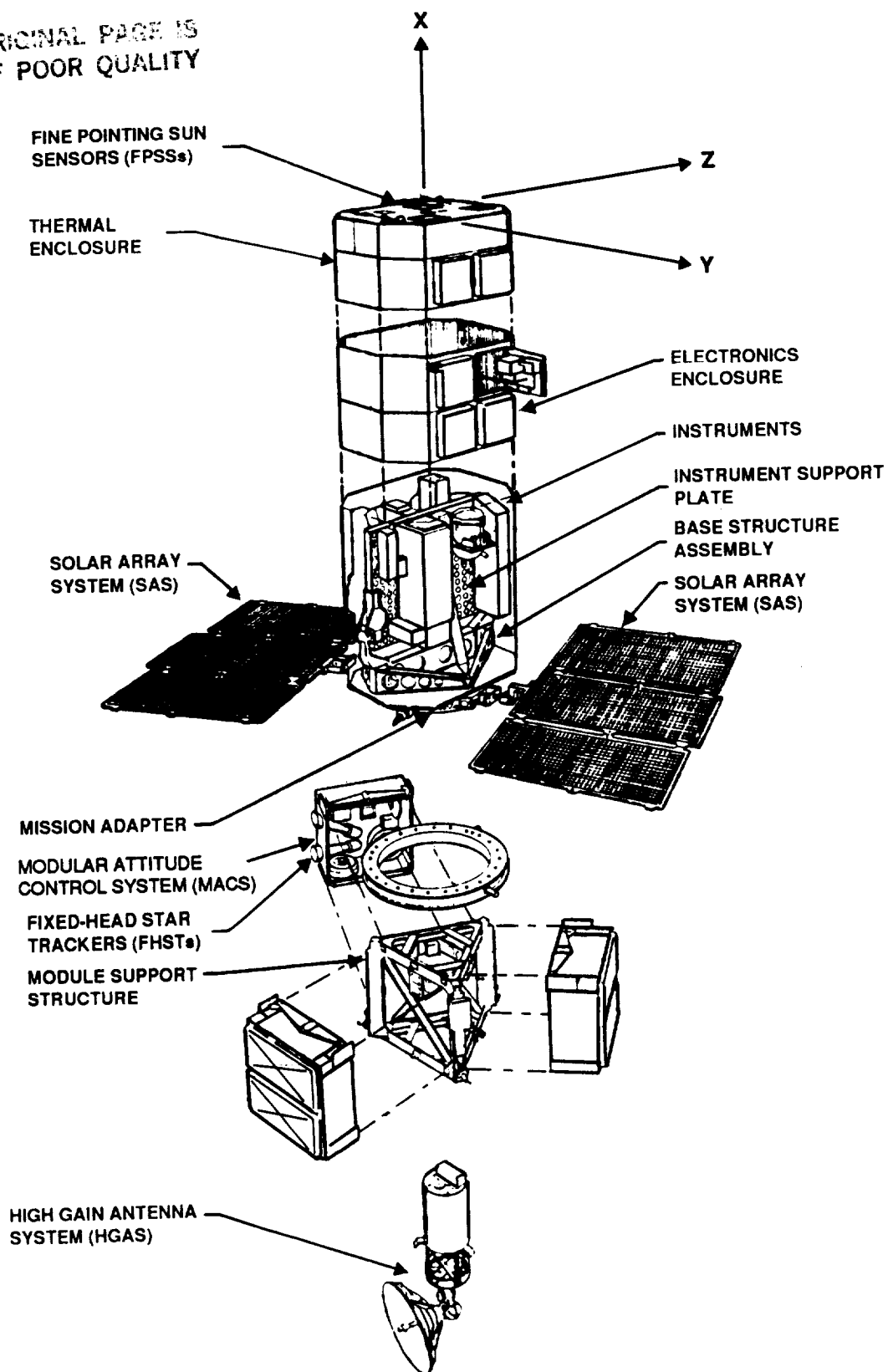


Figure 1. SMM/MMS Structure

The experiment module contains all the SMM mission-specific components. The two main types of components are the SMM scientific instruments and the mission-specific attitude sensors. The instruments comprising the scientific payload mainly study the emissions of the Sun on several different wavelengths, including x-ray, ultraviolet, and gamma ray. The mission-specific attitude sensors are the coarse Sun sensor (CSS) and the FPSSs. The FPSSs are the primary sources of solar pointing information in the normal mission mode, so their colocation with the scientific instruments makes sense. The two separate modules are connected by a mission adapter ring as shown in Figure 1.

The FPSS, a vector sensor, outputs rotations, α and β , about two sensor axes. It has a 2-deg-by-2-deg field-of-view (FOV). The specified accuracy of the FPSS is 5 arc-seconds (arc-sec) (3σ) within a 1-deg square FOV (Reference 2). The FPSS is mounted on the instrument support plate (ISP). The normal to the ISP is parallel to the y-axis of the spacecraft body frame, as shown in Figure 1.

The spacecraft body coordinate frame is defined by the orientation of the FPSS (Reference 2). The x-axis (roll) of the body frame is defined as parallel to the boresight of the FPSS. The y-axis (pitch) and z-axis (yaw) of the body frame are parallel to the FPSS axes. This definition of the body frame facilitates the calculation of the spacecraft pitch and yaw by the FPSS. The spacecraft pitch and yaw attitude may be read directly from the FPSS readings. Thus, at nominal (zero) roll, the spot on the Sun where the spacecraft is pointing may be easily obtained. However, because of this orientation, the FPSS provides no resolution on the roll attitude of the spacecraft. Also, since the FPSS nominally defines the body frame, no alignment calibration of the FPSS is necessary. The only calibration of the FPSS is for the electronic angular response curve of the sensor.

The FHSTs are also vector sensors. They are mounted in the MACS in the MMS section of the spacecraft. The FHSTs have a two-axis sensor coordinate system, with an 8-deg-by-8-deg FOV. Star positions are output in the telemetry as projected angles in the FHST coordinate frame. These values are then converted to a vector and transformed to the body frame by the FHST alignment matrix, S . Since the FPSS defines the body frame, S represents the relative alignment of the FHST and the FPSS, called the coalignment. The position accuracy of a single FHST measurement is 30 arc-sec (3σ) (Reference 2). This noise in the observation is mainly due to instrument temperature and the varying magnetic field of the Earth.

Since there are two well-separated FHSTs, a full three-axis attitude may be obtained solely from FHST data. However, in August 1987, FHST 2 experienced a loss of power and became inoperable. Hence, the quality of the FHST-only attitudes became significantly degraded. Since star observations in the sensor FOV are only separated by a maximum of 8 deg, poor attitude resolution about the FHST boresight axis resulted; thus, after the failure of FHST 2, FHST-only attitudes were of minimal use. Consequently, the analysis in this paper is concerned only with the FHST misalignment behavior before August 1987.

The FHSTs collect data by tracking stars in the FOV. A single star will be tracked for several (N) observations. These N observations are combined to form a track group,

which is the average position of the star in the FHST FOV. Thus, reduction in the uncertainty of the track group position can be averaged out by using

$$\sigma = 30/(N)^{1/2} \quad (1)$$

After a track group is formed, the FHST moves to another star and tracks the new star until another track group is formed. This process continues until the FHST becomes occulted.

The sampling rate of the star observations in telemetry and, therefore, the number of observations per track group, is set by the spacecraft telemetry mode. In science mode (the nominal operational mode) the number of observations that form a track group ranges from 6 to 20, while in engineering mode, 60 to 120 observations are available per track group. Engineering mode telemetry, however, does not contain experiment data. Thus, it is requested only for occasional calibration activities when the high FHST sampling rate can be justified. Because of this restriction, the accuracy of the attitude solutions computed from FHST data approximately ranges from 10 to 30 arc-sec (3σ), depending on the quality of the track groups and the degree to which the alignment matrix, S , is known.

Since, as stated previously, the FPSS is not able to determine the spacecraft roll, the FHSTs are the only source of fine roll determination. A coarse roll can be determined from magnetometer data; however, typical accuracies of the coarse-determined roll are between 1 and 2 deg, much larger than the specified roll accuracy of 0.1 deg. Thus, it is important to compute accurate coalignments of the FHSTs so that the computed roll is as accurate as possible. The nominal alignments of the FHSTs are the original design alignments. The calibrations are performed to calculate the misalignment from the nominal alignments.

The misalignment of the FHSTs has two components. The first component is the misalignment of the sensors with respect to the coordinate frame of the MACS. The second component is the misalignment of the MACS frame with respect to the body frame. Because of problems in observability of the orientation of the MACS frame, these components are combined into one set of values for the misalignment.

For the SMM, the misalignment matrices, M_i , represent the change in the alignment from the original design alignments, S_{oi} , where $i = 1$ or 2 , depending on which FHST is being calibrated. The alignment matrices, S_i , of the FHSTs can then be represented by

$$S_i = M_i S_{oi} \quad i = 1, 2 \quad (2)$$

Since the S_{oi} are known, the purpose of the FHST alignment calibrations is to compute the M_i . The calibrations are performed by taking observed vectors from the three sensors, one FPSS and two FHSTs, and comparing them to the respective reference vectors. The theoretical aspects of the SMM alignment calibrations have been presented in Reference 3 and will not be presented here. This alignment calibration scheme has typically yielded accuracies of 5 to 10 arc-sec in the relative alignment of the FHSTs if engineering mode telemetry is used in the calibration.

2. ANALYSIS

2.1 POSSIBLE CAUSES OF THE MISALIGNMENT VARIATION

Immediately after the SMM repair mission, the new FHST alignments were computed and used in the onboard and ground software. Thus, when pitch and yaw solutions were calculated by the FPSS and FHSTs separately, the resulting differences between the two solutions were initially very small, on the order of the position accuracy in the FHST. However, over the approximately 1-week period before the next alignment calibration was performed, a variation of the differences in yaw attitude, computed separately by the FHSTs and the FPSS, was exhibited that was clearly not random and was well in excess of the FHST solution accuracy (Reference 4). This initial variation is shown in Figure 2. Note that, as shown in Figure 3, the pitch differences show no such variation. Subsequently, to keep track of this variation, although the alignments were recalibrated, the original calibrated alignments were kept on hand and used to process a segment of data each day. The magnitude of the variation eventually reached 120 arc-sec, approximately 8 times greater than the original prerepair estimate for the alignment variation (Reference 5). Obviously, an unmodeled effect was causing this variation.

Several causes were proposed to account for the variation in misalignment:

- Spacecraft bending due to solar radiation pressure
- Electronic or mechanical changes in the sensors
- Uncertainty in the attitude solutions
- Mounting-plate expansion and contraction due to thermal effects

The first possible cause was eliminated because the effects would be too small to measure. Solar radiation pressure, while being a significant effect on spacecraft appendages, will not bend the body of a rigid spacecraft more than a fraction of an arc-second.

The next possibility is electronic or mechanical changes in the sensors themselves. Since the FPSS response was calibrated frequently and since the agreement between FHST readings did not exhibit measurable variations, the change in sensor response was ruled out. The FPSS response did show changes on the order of 1 to 2 arc-sec per month (Reference 4). This small change would not account for the 120-arc-sec differences being observed. An effect related to changes in the sensor, redefinition of the FPSS null, (zero pitch and yaw), occurred once in December 1984. Because of the manner of the FPSS angular response calibrations, the accuracy of the null of the FPSS is not determined directly. The null of the FPSS is defined as the output of the FPSS at the center of the Sun. Some of the experiments are capable of estimating the errors in their solar pointing. These readings have always been measured by the scientific personnel and communicated to the FDF personnel, who incorporated them into the FPSS response function. Because of changes in the electronic response of the FPSS, the null shows time-dependent shifts. Since scientists noticed a significant error in the FPSS null, it was redefined in December 1984 (Reference 4). This caused a significant (20 to 30 arc-sec) change in the

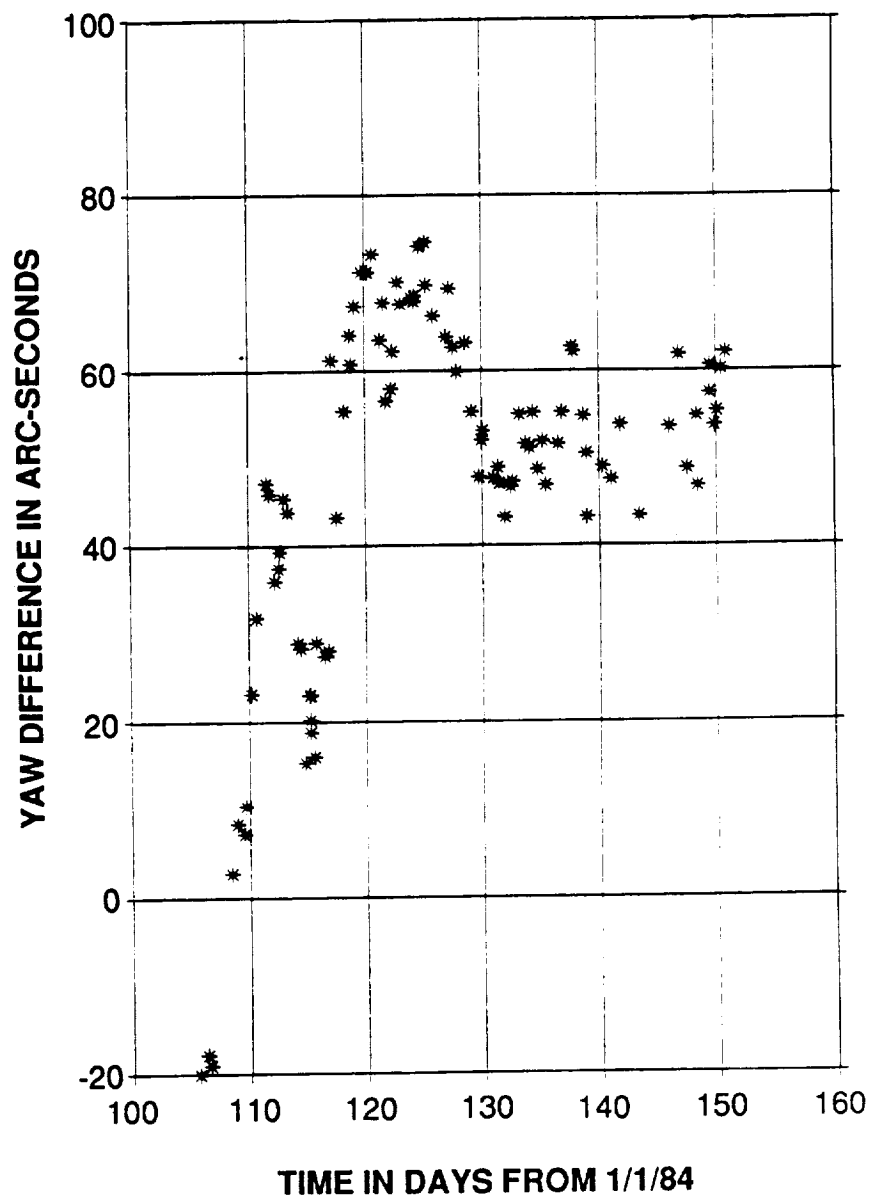


Figure 2. Initial Yaw Misalignment Variations

misalignment of the FHSTs. This shift in the FPSS null was most likely accumulated over the time since the repair mission. However, because of the manner in which the FPSS calibrations are performed, it could not be accounted for until the discrepancy was noticed by the scientific instruments. The effect of the null shift can be most clearly seen in the pitch misalignment data, shown in Figure 3. Note that the discontinuous drop at approximately day 350, which apparently reversed the accumulated drift from day 100. This same effect occurred in the yaw misalignment data; however, the discontinuous change was not significant enough to show clearly on the plot. This, however, serves the purpose to show that the effect would not be completely responsible for the misalignment variation.

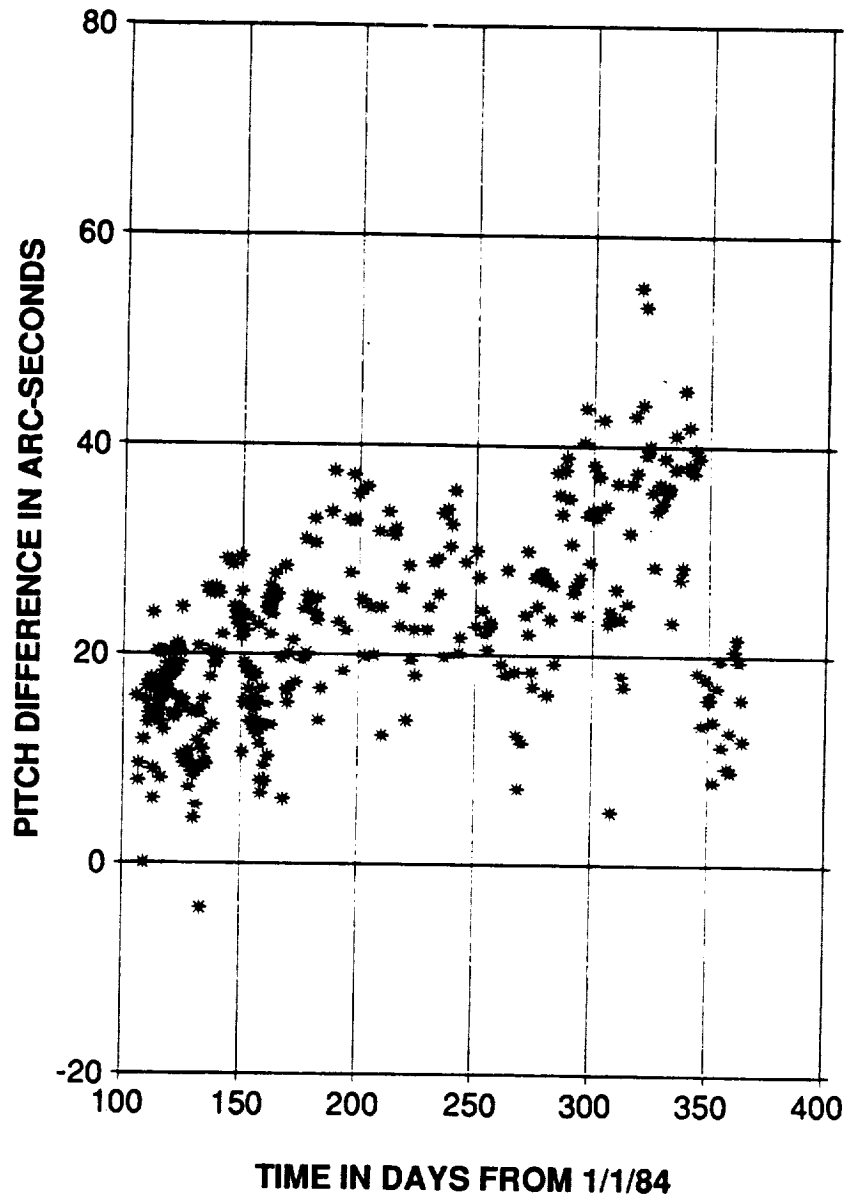


Figure 3. Pitch Misalignment Variation

The third possibility is the uncertainty in the attitude solutions. As mentioned previously, the misalignment variations were measured daily using FHST and FPSS attitudes computed during normal operations. This attitude comparison does not accurately determine the misalignments. More accurate results would have been obtained by performing frequent FHST calibrations; however, that approach was deemed unfeasible because of the resources required and the need to interrupt scientific observation to increase the FHST sampling rate during calibration. Hence, the less accurate but much quicker method of subtracting the computed attitudes was devised. The disadvantage is that a noise level is introduced that is equal in magnitude to the uncertainty of the less accurate attitude solution, which is the FHST attitude. Thus, a noise level of 20 to 30 arc-sec was expected

in the misalignment variation plot. However, this noise would not explain the observed variation because it is random, as compared to the observed patterned variation, and its magnitude is approximately one sixth of the magnitude of the observed variation. It is also worth noting that as full in-flight calibrations were performed, the results were completely consistent with the daily attitude calculations.

The effect of temperature variation on attitude sensor alignments has been seen on previous missions, most notably the Magnetic Field Explorer (Magsat) (Reference 6). Thus, the possibility of bending due to thermal effects was explored by checking various temperatures in the spacecraft. It was found that temperatures on the ISP and the mission adapter ring showed a variation over time that was similar to the variation seen in the yaw misalignment. Six temperatures were initially monitored; however, since all six showed the same basic variation, only one was used for graphing and statistical purposes. Since the temperatures were available in the spacecraft telemetry, they could easily be recorded from all real-time station contacts. The temperatures varied slowly over time, taking at least several orbits to change measurably. After this determination was made, data were collected for yaw misalignment and temperature only once per day. The variation of the temperature superimposed on a graph of the variation of the yaw misalignment is shown in Figure 4. The relative scales in the plot were chosen by performing a fit of yaw differences to temperature. The correlation is obvious. Figure 4 shows only 8 months of data to accentuate the correlation. However, all data taken between the SMM repair and the FHST 2 failure exhibited this trend.

The similarity of the two variations points to spacecraft thermal bending as the cause of the misalignment variation. Thus, the changing spacecraft temperatures cause a temperature gradient which, in turn, causes the spacecraft structure to bend. A temperature gradient requires two temperatures. However, because of a lack of thermocouples on the spacecraft, no other temperature, which when set up as a gradient with the ISP temperature resulted in a variation similar to the yaw misalignment. However, since the single temperature variation correlates so well with the yaw misalignment, it can be postulated that the second temperature remains basically constant (i.e., heat-sunk to the spacecraft chassis). In other words, the variation of the ISP temperature is equal to the variation of the temperature gradient.

The pitch misalignment never showed any significant patterned variation similar to the yaw misalignment variation. As shown in Figure 3, the variation seems to have a noise level of 20 to 30 arc-sec, a slow drift over several months, and a major shift at the point of the FPSS null redefinition. Thus, it seems the dominant effects in the pitch misalignment variation are the uncertainty of the FHST attitude solutions and the shift in the FPSS null.

The fact that the thermal profile variations seemingly do not affect the pitch misalignment can possibly be explained by the orientation of the ISP and the mounting of the FPSS on the ISP. As shown in Figure 5, the ISP is aligned along the z-axis (yaw). The FPSS is mounted in the middle of the ISP, right on the y-axis (pitch) and off-set from the z-axis. Thus, bending of the ISP translates directly into rotation of the FPSS about the yaw axis. Conversely, bending of the ISP will not cause any rotation about the pitch or roll axes.

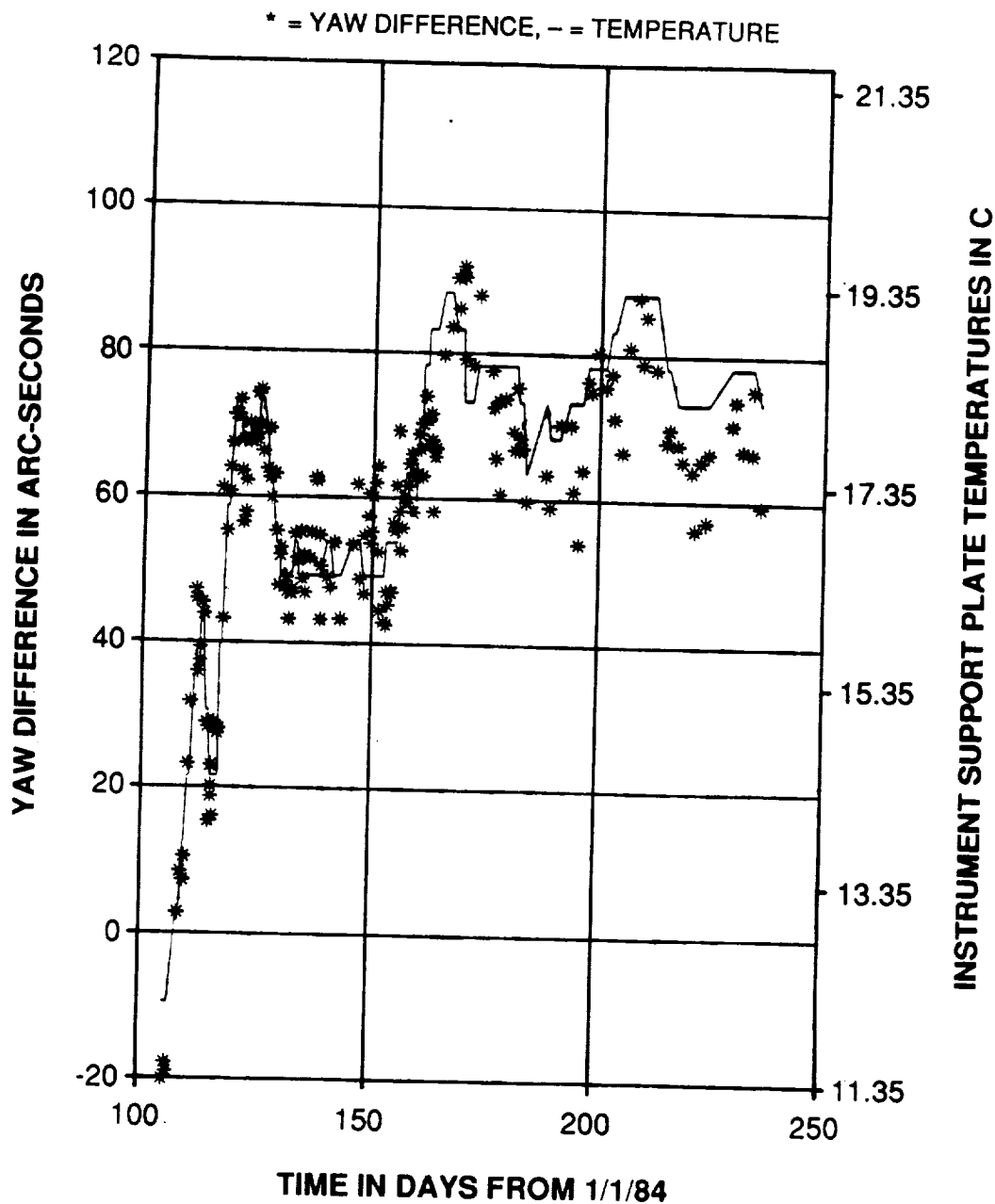


Figure 4. Yaw Attitude Differences and Instrument Support Plate Temperatures

Therefore, this analysis suggests that it is the FPSS that is actually moving. This causes a strange situation in that it is the movement of the FPSS that is causing the misalignment of the FHSTs. This peculiarity can be removed when it is realized that the FPSS defines the body-frame coordinates and, in fact, provides the most critical pointing information for the experiments. Thus, the movement of the FPSS causes the body frame to rotate, which, in turn, causes the FHST misalignment to change. Therefore, the FHSTs never really experience any significant motion with respect to the spacecraft chassis; it is the moving body frame that causes the alignment of the FHSTs to change. Presumably, the

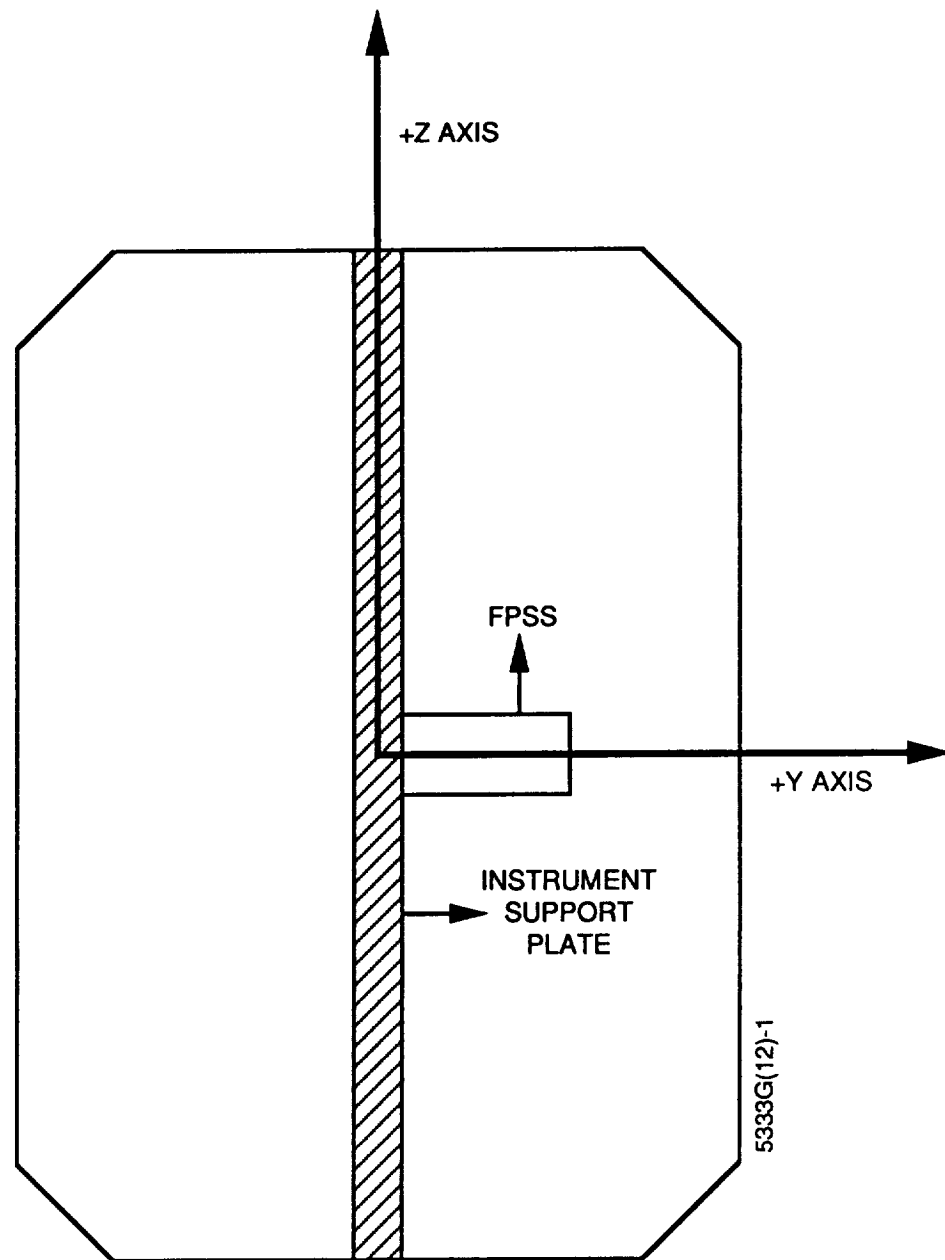


Figure 5. Orientation of Instrument Support Plate and FPSS

other attitude sensors on the spacecraft, such as the three-axis magnetometer, experience this same phenomena. However, because of the low accuracy of these instruments, this phenomena cannot be seen in their alignments. This analysis is a possible explanation of the misalignment variation. However, the full structure of the spacecraft would need to be analyzed before any explanations of the variation could be proved.

2.2 YAW MISALIGNMENT ESTIMATION FROM THE TEMPERATURE PROFILE

Since the dominating factor in the FHST misalignment variation about the yaw axis is the variation of the temperature, it would seem likely that the misalignment could be esti-

mated from the observed temperature, thus reducing the need for in-flight FHST alignment calibration. The first step was to set up a scatter plot of the yaw misalignment versus the temperature. This scatter plot, shown in Figure 6, shows a nearly linear

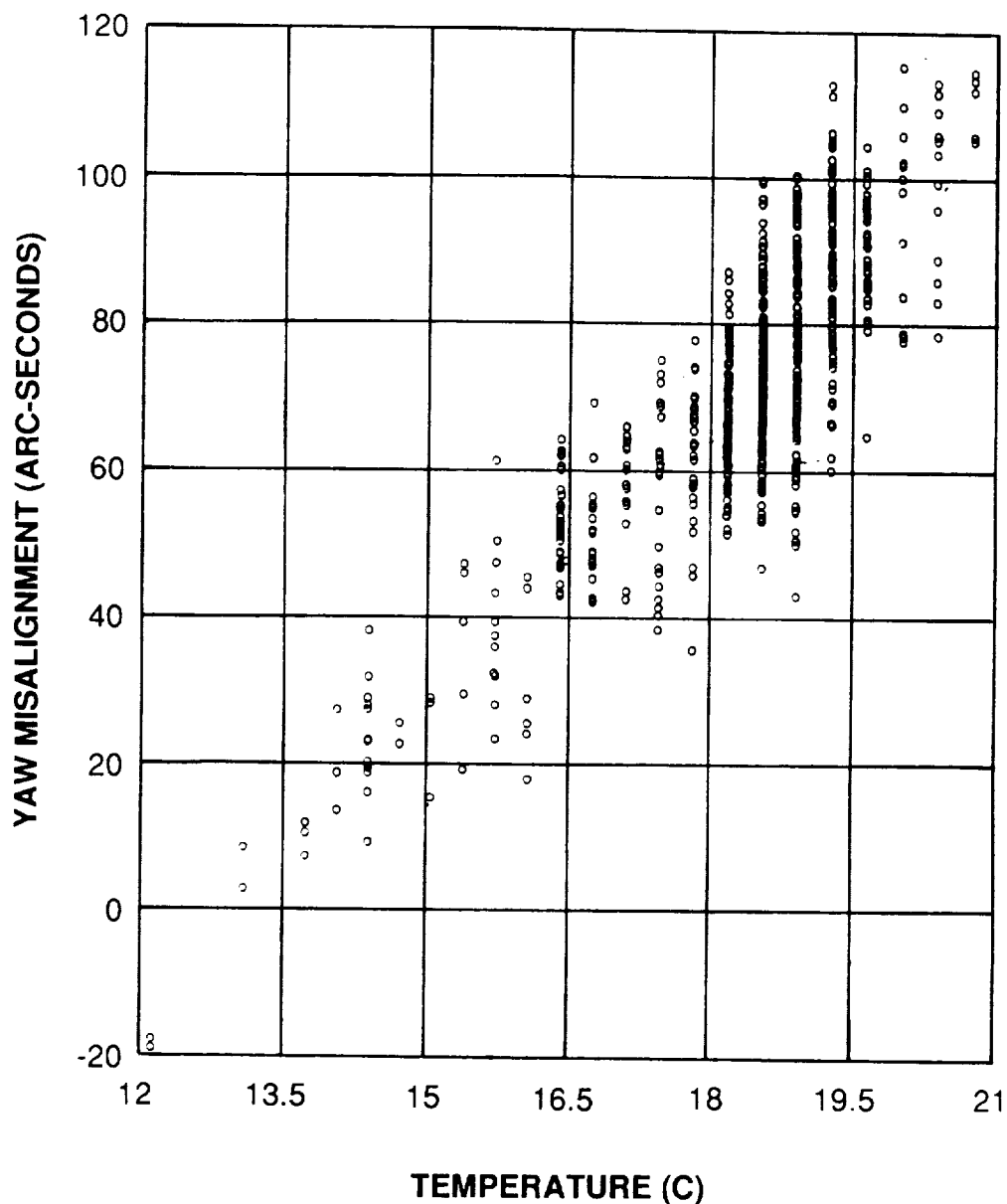


Figure 6. Yaw Misalignment Versus Temperature

relationship between the yaw misalignment and the temperature. A linear least-squares fit was performed on the data, and the resulting equation was

$$M = 13.410 * T - 173.790 \quad (3)$$

where M is the scalar yaw misalignment and T is the temperature. The root mean square (RMS) residual of the straight line fit was approximately 10.5 arc-sec, thus 99.7 percent

of the yaw misalignments calculated from the function in Equation (3) would be within 31.5 arc-sec (3σ). The error (1σ) in the slope is 0.3 arc-sec per deg celsius and the error (1σ) in the y-intercept is 5.6 arc-sec. This fit could be incorporated into the attitude determination system to estimate the misalignment matrix so that a more accurate attitude could be determined.

A more accurate fit may be determined if the effect due to the null shifts is taken into account. As shown in Figures 7 and 8, the data in Figure 6 can be broken down into two segments: data starting at the SMM repair mission and running until the date of the null shift in December 1984, and data starting at the null shift and running until the failure of FHST 2. Figures 7 and 8 show two different functions. Fits were done to the two functions and the equations were

$$M_1 = 10.801 * T - 130.029 \quad (4)$$

$$M_2 = 15.721 * T - 215.072 \quad (5)$$

The error (3σ) of the calculated misalignment in Equation (4) is 25.5 arc-sec, the uncertainty (1σ) in the slope is 0.3 arc-sec per deg, and the uncertainty (1σ) in the y-intercept is 5.9 arc-sec. The error (3σ) of the calculated misalignment in Equation (5) is 31.1 arc-sec, the uncertainty (1σ) in the slope is 0.5 arc-sec per deg, and the uncertainty (1σ) in the y-intercept is 7.6 arc-sec.

Equations (4) and (5) have different slopes, which poses an interesting question. Since the null shift is a change in the position of the boresight of the tracker, one would think this would be reflected as a change in the constant term of the misalignment function only. While a significant change in the constant term of these equations exists, the change in the slope indicates that the dependence of the misalignment on the temperature is changing. This would indicate that the equation for the estimate of the alignment would need to be calibrated. This would seem to undermine the estimate, since its prime use would be to replace FHST alignment calibration. However, since the variance improved by only about 2 arc-sec for the first segment, calibration of this equation would probably not exceed once per year.

2.3 SUGGESTIONS FOR SPACECRAFT OPERATIONS

It has been shown that as temperatures in the SMM structure vary; the yaw misalignments of the FHSTs vary similarly, thus degrading the accuracy of the attitude solutions. To compensate for this effect, two methods of solution are available: (1) frequent in-flight alignment calibration and (2) misalignment function modeling. Both methods have their advantages and disadvantages.

The advantage of frequent in-flight calibration is that immediately following the calibration, the resulting alignments are known to a high degree of accuracy, better than 15 arc-sec. However, this accuracy will degrade over a couple of weeks as the temperature varies. This problem can be overcome by recalibrating the alignments every 2 to 3 weeks. However, this points out the major disadvantage of this scheme: in-flight calibration of the

YAW MISALIGNMENT VS TEMPERATURE

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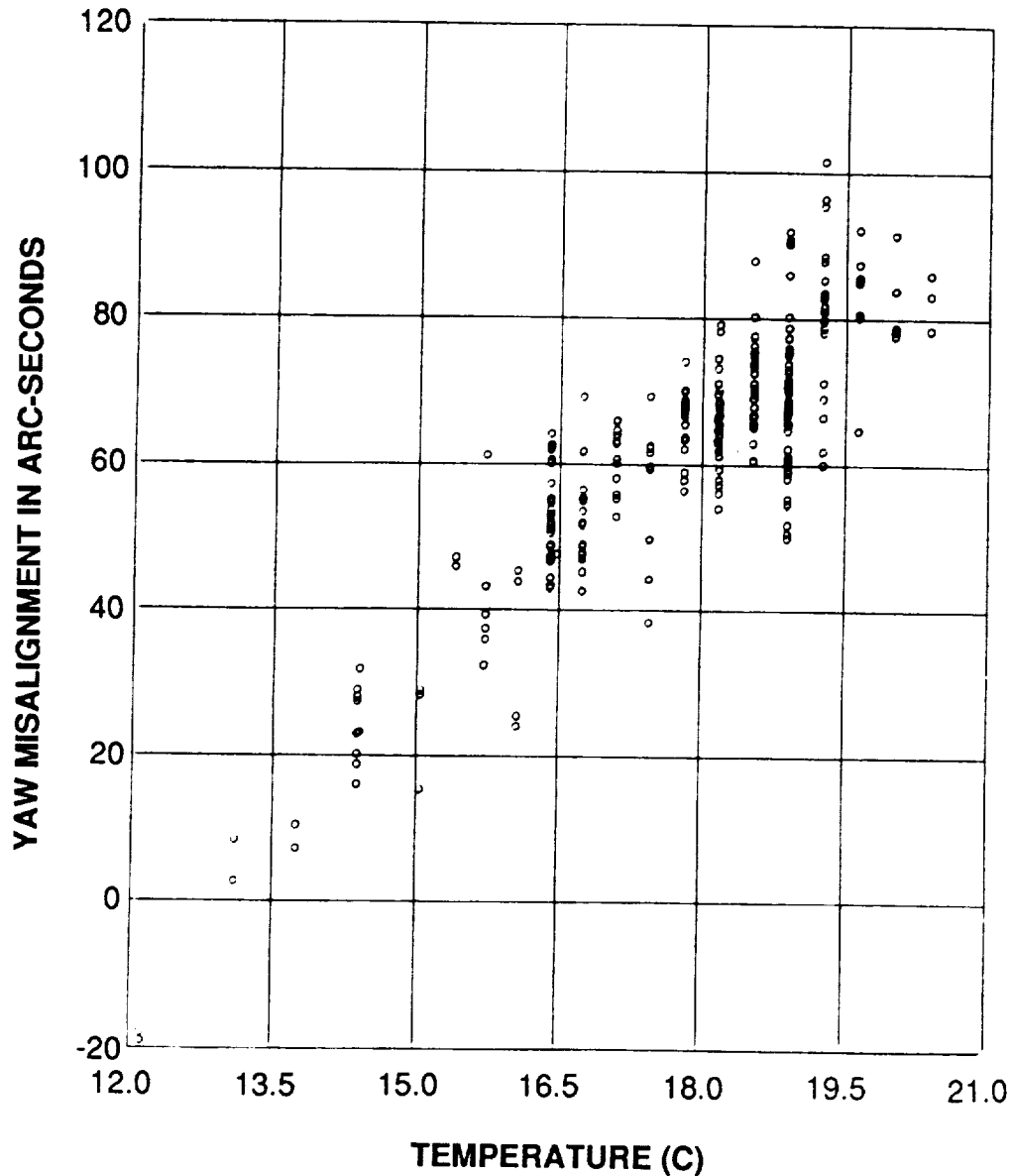


Figure 7. Yaw Misalignment Versus Temperature Before Null Redefinition

FHST misalignment requires operational time, typically three orbits, on the spacecraft and the ground and, in the case of the SMM, requires the use of engineering mode telemetry. Time spent calibrating the attitude sensors is lost to the scientists. Thus, ideally, these type of calibrations should be performed infrequently, perhaps no more often than every 2 months.

On the other hand, modeling of the misalignment function requires calibration of the function at most once a year. These calibrations of the function require no special operational time of the spacecraft; they can be completed during routine processing of the

YAW MISALIGNMENT VS TEMPERATURE

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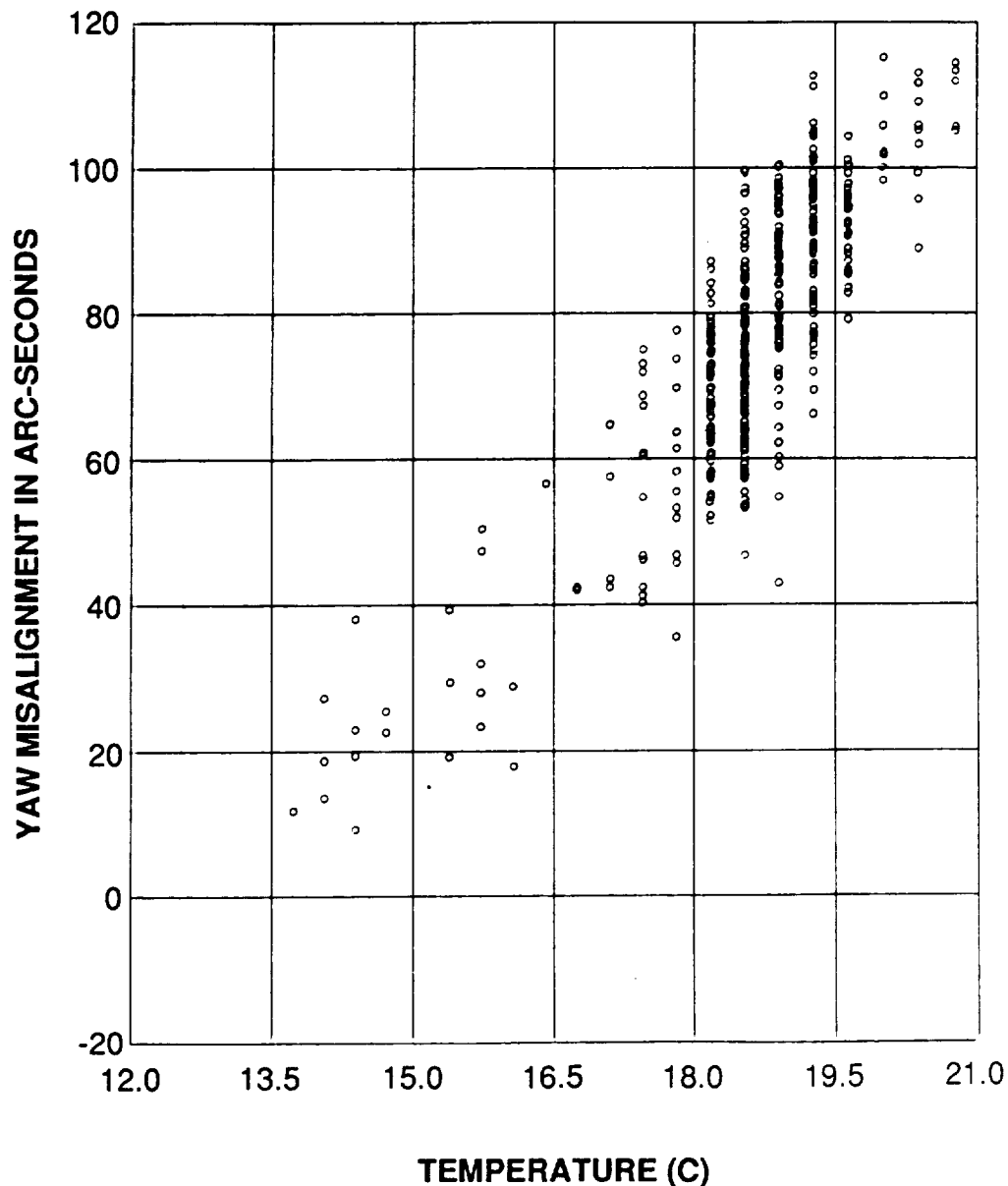


Figure 8. Yaw Misalignment Versus Temperature After Null Redefinition

attitude data. However, the disadvantage of using the misalignment function is slightly degraded knowledge of the misalignments, between 5 and 15 arc-sec less accuracy than the in-flight calibration.

For best results, it is suggested that a combination of the two methods be used. The in-flight calibrations should be used initially to determine an accurate estimate of the misalignment matrix, M , and the misalignment function should be used to monitor the changes in M . Then, every 6 months to 1 year, the alignment calibration should be re-done, using the in-flight method to maintain the most accurate estimate of M . This

scheme combines the advantages of both methods by using as little operational time as possible and maintaining a high degree of knowledge of the FHST alignment matrix.

For example, the SMM could use the following scheme. The postrepair FHST alignments could be calibrated using the in-flight method. Then, the yaw misalignment function could be used to maintain the yaw misalignment accuracy. The pitch and roll misalignment would not need to be maintained because their misalignments are not affected by the varying temperatures as stated previously. The changes in these misalignments due to the other factors are much smaller and could be maintained by the in-flight calibrations every 6 months.

2.4 MODELING THE TEMPERATURE DATA

The relevant temperatures on the SMM are received from the spacecraft telemetry; thus, the misalignment can be easily calculated from the simple models presented previously. However, for missions where the relevant temperature data are not available in the telemetry or where the configuration of the mission is substantially different from the SMM, the previously presented analysis needs to be supplemented by other sources of data.

For missions with a similar configuration to the SMM but for which temperatures are not available in the telemetry, an analysis of the temperature profile of the SMM shows that the profile can also be modeled simply. For the SMM, the temperatures on the ISP and the mission adapter ring are a function of instrument activity, distance from the Sun, and the length of the spacecraft day. The attitude of the spacecraft, of course, plays a large part in the profile. However, the SMM maintains nearly the same attitude relative to the Sun so that the temperature does not vary due to this effect. Therefore, this effect is not taken into account in this analysis. However, for missions with attitudes that are dynamic relative to the Sun, i.e., Earth-pointing or astronomical missions, this effect should also be modeled.

As seen in Figure 9, the dominating effect on the spacecraft temperature is payload instrument activity. Operating the scientific instruments generates a great deal of heat that is dissipated and radiated to other parts of the spacecraft. The temperature profile experiences major changes along with changes in instrument activity. At the repair of the SMM, approximately day 100 of 1984, all the payload instruments were off, and, as seen in Figure 9, the temperature was very low. As the mission started scientific activities, the payload instruments were turned on, and the temperature rose rapidly. Another example is seen later near day 250 when the spacecraft went into safehold mode and all the scientific instruments were powered off. For the SMM, safehold mode is the spacecraft's response to a perceived dangerous situation. The MACS safehold electronics takes attitude control from the OBC and holds the spacecraft in a Sun-oriented attitude until the problem is resolved. To conserve spacecraft power, most of the instruments are, consequently, powered off. Thus, the temperature of the spacecraft drops quickly.

Since the temperature changes in the case of powering on and off of the payload instruments occur relatively quickly, this effect can be modeled as a step function. The size of the step will vary with the number of instruments that are powered off. This component of the temperature profile is shown in Figure 9.

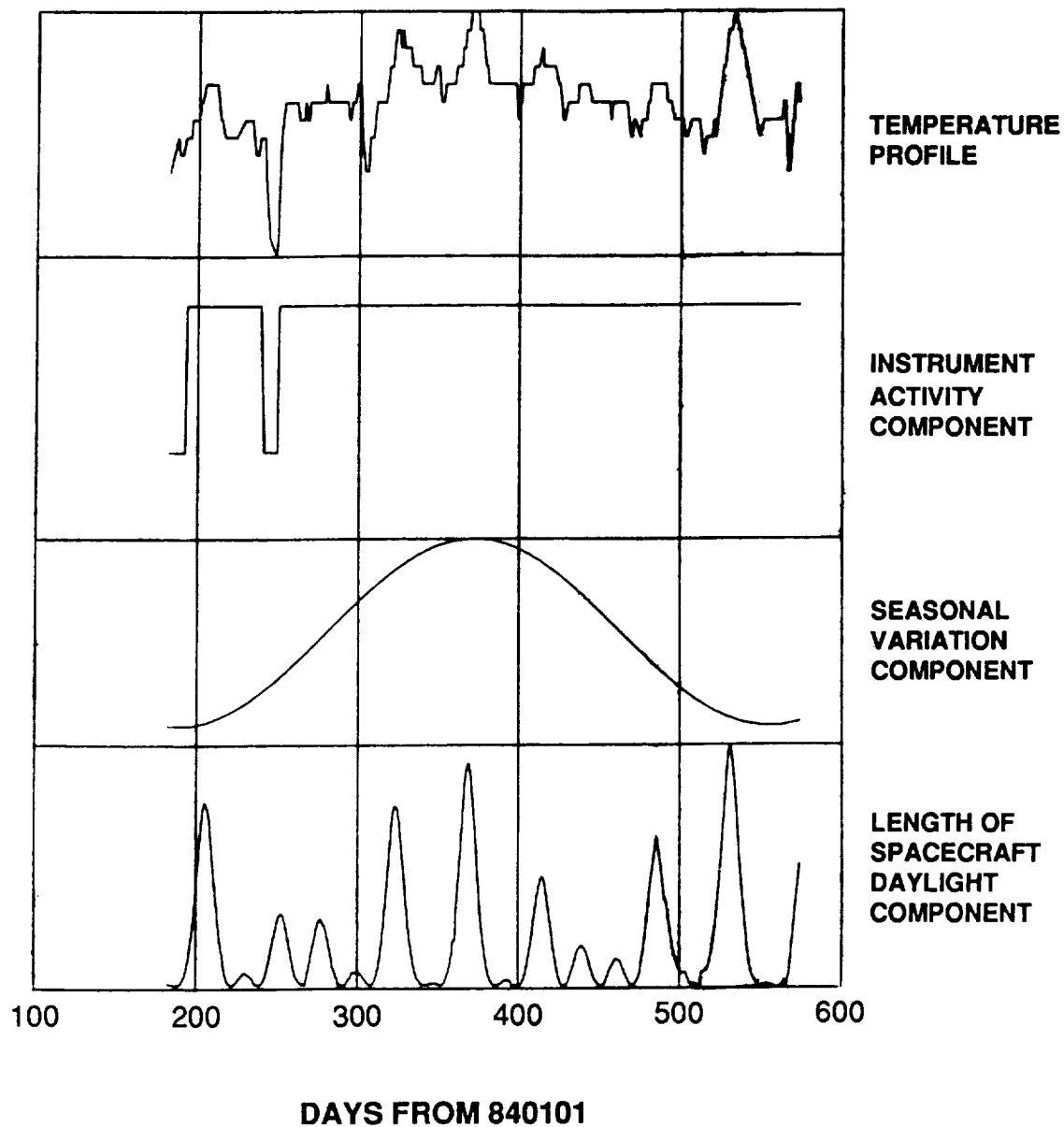


Figure 9. SMM Temperature Profile and Components

Another effect on the SMM temperature profile is the distance of the spacecraft from the Sun. This is a consequence of the Earth's orbit about the Sun. The Earth's orbit is not exactly circular, having an eccentricity of 0.016. Thus, the spacecraft is closer to the Sun in December at the Winter Solstice and farthest from the Sun in June at the Summer Solstice. This effect can be modeled by a sinusoidal pattern with a period of 1 year. The contribution of this effect on the SMM is shown in Figure 9.

The last effect on the temperature profile is the variation in the length of the spacecraft daylight period. The spacecraft daylight period is the amount of time per orbit that the

spacecraft is in view of the Sun. This varies due to the geometry of the orbit. Orbit dawn is defined as the beginning of the spacecraft daylight period, i.e., the time when the spacecraft becomes unblocked from the Sun by the Earth, and orbit dusk is defined as the end of the spacecraft daylight period. Then, orbit noon is the middle of the daylight period, the time exactly between orbit dawn and orbit dusk; orbit midnight is the time exactly between orbit dusk and orbit dawn. Due to geometrical considerations, the maximum time of the spacecraft daylight period is when the right ascension of the ascending node of the spacecraft is at orbit noon or midnight. This causes the declination of the spacecraft orbit to be a maximum near orbit dusk and dawn. The spacecraft crosses a shorter chord of the Earth at the higher declinations; thus, the effective amount of Earth that is blocking the Sun from the spacecraft is less. Consequently, orbit dawn occurs earlier and orbit dusk occurs later. The effect also has a seasonal component, being more pronounced near the solstices, as shown in Figure 9.

This effect is completely dependent on the orbit parameters and can be solved for exactly if the spacecraft ephemeris is known. If the mission is in the planning stages, the effect can be modeled from the preliminary knowledge of the orbital elements. This component of the temperature profile for the SMM is shown in Figure 9.

Once the effect of these parameters is taken into account, the total temperature profile can be formed. Then, after investigating the mission configuration and its response to temperature variation, an approximate function, analagous to Equations (3) through (5) can be determined. This function can be used in the premission attitude stability, determination, and control planning and the early mission operations. During the mission, data would be collected over a sufficiently long baseline to completely specify the model; if the SMM can be used as a guide, a minimum of 6 months would be required to account for the seasonal effects. Clearly, this approach requires substantially more intensive analysis than the use of direct temperature measurements.

3. SUMMARY AND CONCLUSION

In summary, flight data from the SMM mission attitude determination support demonstrates that spacecraft attitude sensor alignments vary with spacecraft temperature by up to 120 arc-sec over a 1-year period, with the majority of the variation occurring during the first few weeks as the temperatures stabilize. These levels are about eight times greater than were indicated in the currently available reports on the prelaunch thermal structural stability of the SMM. Methods have been proposed to incorporate flight measurement of the temperature-versus-alignment function and its variance to operational procedures with the benefit of reducing the spacecraft operations time required to support attitude sensor alignment calibration. Also, combining an approximate model of the temperature with the model of the alignment-versus-temperature could provide a significant reference for planning and analysis currently in progress for future missions. This prelaunch planning should also include incorporating the spacecraft structure temperatures in the attitude telemetry record.

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